# RESONANT MULTI-GAP FUNNELING AND DE-FUNNELING SYSTEMS

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## 1 INTRODUCTION

At present the ESS super-conducting option is under consideration, where the linear accelerator is divided into two main parts: the low energy part up to 100 MeV and the high energy super-conducting part from 100 MeV to 1333 MeV. The only change of frequency just after the funnelling allows filling each separatrix in the accelerator, which results in the smaller number of particles in each bunch and makes easier to fulfill the particles losses requirements. Simultaneously the funneling helps to reach the required beam intensity for ESS of 107 mA in peak per micro pulse. Two identically bunched beams have to be merged into a single beam with double intensity.

We propose the resonant method of the beams funnelling based on the multi-gap deflector /1/. The new idea differs from another ones /2,3/ by the possibility to organize the $\pi$ -mode standing wave deviation system. It is different from another method by the higher efficiency. We have analyzed, designed and compared two types of different H-cavities with the quadrupole TE211 mode and the dipole TE111 mode. They both can provide the effective resonant merging of beams. Additionally, instead of the pulse dividing method into two rings (or more for multi-purposes facilities) this device can be used to split the beam after acceleration into two or three beams and to deliver them to different facilities simultaneously.

## 2 ELECTRODYNAMICS OF FUNNEL DEVICE

*2.1 Dipole or quadrupole mode?*

To provide the transverse electrical field we should install the electrodes inside the cavity.

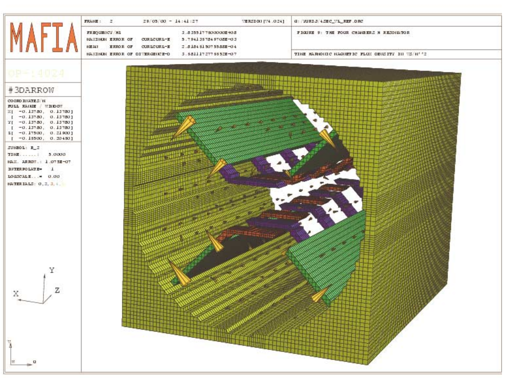



Figure 1: TE211 mode structure

The figure 1 shows the deflector based on the four chambers H resonator excited on the quadrupole mode TE211. The resonator consists of the pipe and four wanes. The wanes divide the pipe on four equal sectors. The deflecting plates are kept to the edge of wane by “legs”. Each pair of wanes forms the sequence of one-polarity capacitors and it interleaves to another pair of wanes with the opposite polarity. Thus, the total sequence of the capacitors forms the lattice with the required change of polarity.

Figure 2 shows schematically the main idea of funnel device based on TE111 mode.

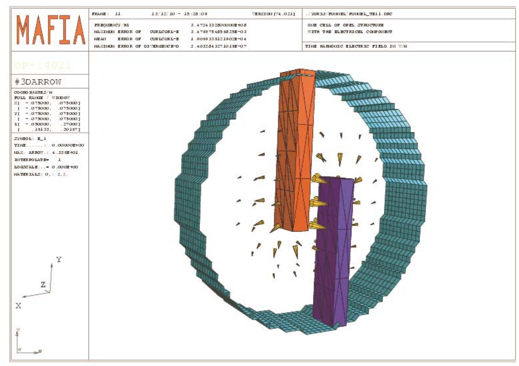



Figure2: One period of TE111 mode structure

The pairs of electrodes are alternately changed by position along the cavity. The magnetic field has one variation in all directions. The magnetic flux rounds the electrodes from above to bellow. The electrical field is perpendicular to the magnetic field and it is directed from left to right. The quasi-electrical field arises in the gap between them, and it is directed top-down. For the next pair the electrodes are changed by position and the quasi-electrical component flips top. Since the longitudinal distance between the neighboring pairs equals to $\beta\lambda/2$, it is exactly the $\pi$ -mode standing wave deviation system for the beam.

The figure 3 shows the transverse electrical field along the funnel device for both modes.

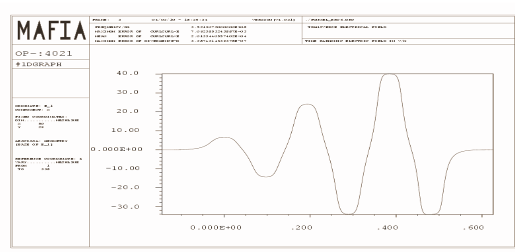



Figure 3: The transverse electrical field in the TE211 and TE111 mode structures

In the empty cylindrical cavity without any electrodes inside (unloaded cavity) the critical wavelength of TE211 and TE111 modes is connected with the radius of cavity

by the ratio $R = \lambda / 2.06$ and $R = \lambda / 3.41$ correspondingly. In result of the electrode's capacity the cavity radius decreases for both modes, but the radius of cavity based on TE211 mode remains to be bigger in comparison with the cavity based on TE111 mode.
In case of 352.2 MHz the ratio between the gap and cavity sizes is quite reasonable, and it is another situation for the lower frequency 176.1 MHz. Since the gap size is determined by the beam parameters as before, but the cavity sizes increase almost by factor of 2, this ratio looks not so optimised. Therefore the dipole mode funnel device is more preferable.

*2.2 Cylindrical or rectangular cavity?*

Due to similarity (see fig.2) with "OPEL" emblem we called this structure by "OPEL"-structure. The insertion of electrodes in the "OPEL" cavity breaks the axial symmetry, and later it initiated us to pass to the rectangular option. The sizes of cavity for this mode take something average between TE211 and TE111 modes. But due to another magnetic field distribution this cavity has the more convenient construction for the tuning and the cooling systems. Figure 4 shows the segment of the rectangular structure from MAFIA simulation.

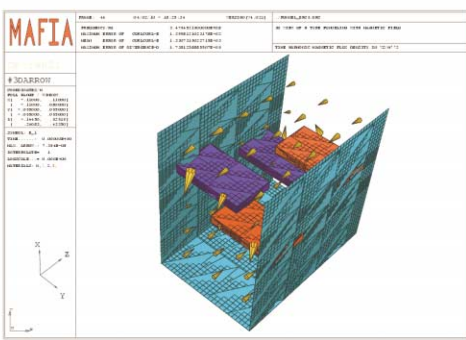
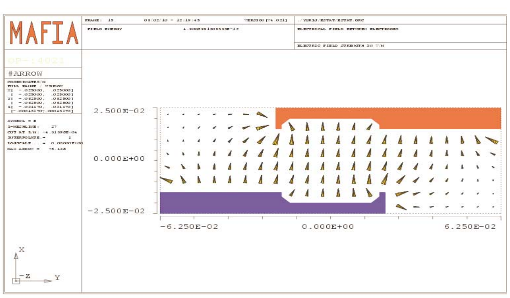



Figure 4: TE101 rectangular structure

*2.3 Electrical field correction*

The number of electrodes pairs depends on the required angle deviation of the beam and the maximum possible field in the gap. In the same time the RF power heating is proportional to the squared amplitude and it could be restricted by the water-cooling system.




Figures 5: Transverse profile of electrodes

The initial gaps have to be wider, since the beams deviation from axis is bigger at entrance. Simultaneously, it is desirable to have the homogeneous electrical field distribution in the transverse plane for all gaps. For this purpose we use the one-dimensional shimming. Figure 5 shows the profile of the electrodes. After shimming the field in the beam region has the deviation $\pm 0.05\%$, what is quite satisfactory from the beam dynamics point of view.

## 3 BEAM DYNAMICS IN FUNNEL DEVICE

*3.1 Space and angle deviation*

Let us represent the transverse electrical field distribution through the series:

$$E_x(z) = \sum_k E_k \sin \frac{2\pi}{\beta\lambda} z. \tag{1}$$

For the even field (without slope along cavity) the angle and space deviations are determined by:

$$\Delta(\frac{dx}{dz}) = \frac{eE_1 \cos\varphi}{2m_0 c^2 \gamma\beta^2} \cdot n(\frac{\beta\lambda}{2})$$
$$\Delta x = \frac{eE_1 \cos\varphi}{4m_0 c^2 \gamma\beta^2} \cdot n^2 (\frac{\beta\lambda}{2})^2 \tag{2}$$

where $E_1$ is the amplitude of the first harmonic, $\varphi$ is the phase of particle relatively of the RF field and $n$ is the number of gaps. In reality (see fig.3) the field has the slope described by formula $E_1 = E_0\left[1 + \frac{\delta E}{E_0} - 2\frac{E\delta}{E_0} \cdot \frac{z}{L}\right]$,

where $L = n\frac{\beta\lambda}{2}$, the angle and the space deviations are:

$$\Delta\left(\frac{dx}{dz}\right) = \frac{eE_1 \cos\varphi}{2m_0 c^2 \gamma\beta^2} \cdot L \text{ and } \Delta x = \frac{eE_1 \cos\varphi}{4m_0 c^2 \gamma\beta^2} \cdot L^2 (1 + \frac{1}{3}\frac{\delta E}{E_0}).$$

Thus, the angle deviation does not depend on the slope value, but the space deviation is bigger for the positive slope.
Unfortunately, in order to increase the geometrical acceptance of the funnel device we have to have the first gap as biggest one and then gradually we decrease the gap width with the number. But it is known that in the H structure cavity the quasi-potential is constant and, consequently, the electrical field has just exactly the positive slope. In reality it is not significant effect, since even at the ratio $1{:}3$ between the first and last gap sizes the space deviation is changed on 50/3 % only.

*3.2 Coupling between longitudinal and transverse motions*

You can see from (2) the particle deviation depends on the RF phase $\varphi$. It is the most important factor causing the emittance growth. We have calculated the trajectories for the case, when the coasting bunch with the length of $2\pi$ is launched on the entrance of the funnel device, and we observed the beam on the exit. Obviously, the particles are grouped around "0" and $\pi$ phases, and the emittance growth is proportional to the average value of deviation: $(\frac{\Delta x}{\Delta x'}) \approx (1-\frac{\cos\Phi}{2})$. For the beam with the length of 20 degrees the emittance grows by $\approx 10\%$, and this value almost does not depend on the number of gaps.

## 4 EFFICIENCY OF DEFLECTOR

Three factors having an influence on the funnel construction are the necessary deviation angle, the maximum field and the maximum RF power absorbed by the cooling system. The multi-gap funnel device has a big advantage over the one-gap device, since the angle deviation is proportional to the squared length of device (number of gaps), and we can get the necessary deviation angle by the appropriate choice of the length. However, simultaneously with the angle deviation the space deviation grows with the length. Therefore the initial gaps have to be more open and the efficiency of funnel device goes down with the transverse field $E \propto \frac{U}{d}$ as well. To characterize the efficiency we introduce the value $Eff = \frac{\alpha^2 L_{cavity}}{P_{RFlosses}}$ measured in the dimension of degree**2/(MW/m). Figure 6 shows the efficiency of the funnel device versus the gaps number for two frequencies 352.2 MHz and 176.1 MHz.

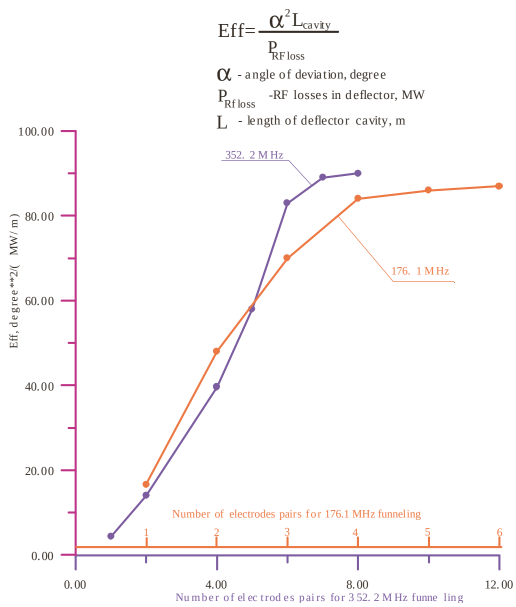



Figure 6: Efficiency of Funnel device

You can see the significant gain of the 5-6 gaps (3-4 gaps for 176.1 MHz) over the one-gap device. But then the efficiency is almost constant. It is because the growth of the gap size is compensating the advantages of the multi-gap device. From this data you can see that in the one-gap device deviating the beam by 2 degrees the RF power 1MW has to be absorbed in CW regime, what is not realistic even for 6 % duty cycle machine like for ESS project.

In principle, just only the one-gap device for 352.2 MHz is restricted by the field maximum, if to deviate the beam by more than one degree. For all another options the main parameter is the power limit absorbed by the cooling system. From this point of view we suggest the six-gap device for the frequency 352.2 MHz and the four-gap device for 176.1 MHz. Both options can work in the high duty cycle regime.

## 5 DE-FUNNELING SYSTEM

In principle, if we know how to merge the beams, then the inverted system has to split the beams. This idea has a chance to be used on the exit of the accelerator to deliver the accelerated particles to many different facilities simultaneously. The bunches, following with the frequency 704.2 MHz and passing through the de-funneling system with the operating frequency 352.2 MHz, are split into two beams with equal intensity. In spite of the angle deviation decreases with the energy the resonator with 10 plates can split the beams by $\pm 1^0$. Such a resonator has the length of 3.9m and at 7.5MV/m requires the power 160 kW.

## 6 CONCLUSION

We have developed the constructions of the funnel device based on the quadrupole mode TE211, the dipole mode TE111in the cylindrical cavity and TE101 in the rectangular cavity. They meet to all requirements of the high duty cycle accelerator facility. The efficiency of the multi-gap RF deflector is by an order of magnitude greater in comparison with the single gap deflector. For both frequencies 352.2 MHz and 176.1 MHz the rectangular construction is more optimal from the tuning and cooling point of view. At present the real construction of funnel device is fabricated in Institute of High Energy Physics in Protvino, which will be tested on the RF test bench.

We would like to thank IKP and ESS scientists for lot of fruitful and stimulating discussions of this device.

## 7 REFERENCES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